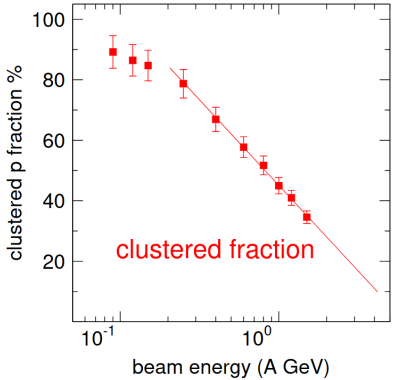
Midrapidity cluster formation within PHQMD approach

V. Kireyeu for the PHQMD team

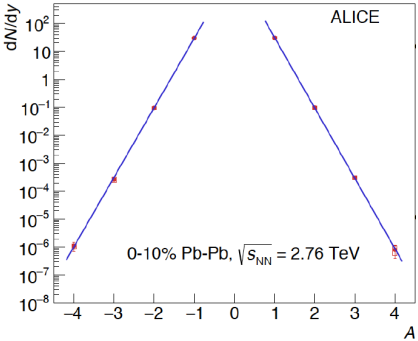
02.12.22

Introduction: the puzzle



Nucl.Phys.A 848 (2010) 366-427

Low energy: up to 20% of protons in central Au+Au collisions at NICA energies are bound into the clusters.

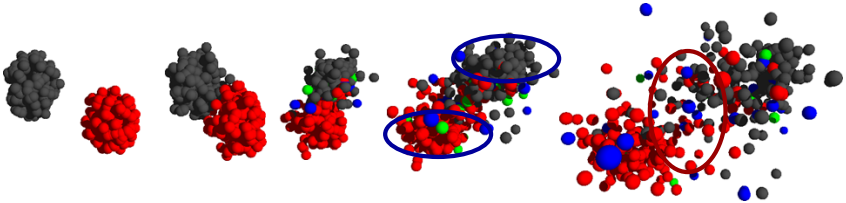


Nucl.Phys.A 971 (2018) 1-20

High energy HIC – "ice in a fire" puzzle: **how the weakly bound objects can be formed in a hot environment?**

Introduction: cluster formation

Projectile/target spectators: heavy cluster formation
Midrapidity: light clusters



IQMD: Ch. Hartnack

(Anti)hypernuclei production:

- at mid-rapidity by Λ coalescence during expansion
- at projectile/target rapidity by re-scattering/absorption of Λ by spectators

Introduction: cluster finding

Static approaches: cluster multiplicity determined at a fixed time or temp

- coalescence (early, assumption: no collisions later)
- statistical model (V,T,N) very late $\rho << \rho_0$

Dynamical approaches: cluster multiplicity is function of time

- minimum spanning tree (correlation in coordinate space)
- simulated annealing (correlation in momentum and coordinate space)
- time-dependent perturbation theory using Wigner densities

PHQMD transport approach

The goal: to develop a unified n-body microscopic transport approach for the description of heavy-ion dynamics and dynamical cluster formation from low to ultra-relativistic energies.

Realization: combined model **PHQMD** = (PHSD & QMD) & MST and SACA

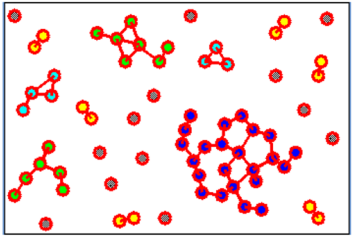
Phys. Rev. C 101, 044905

- **Initialization & propagation of baryons**: Quantum-Molecular Dynamics
- **Propagation of partons (quarks, gluons) and mesons + collision integral** = interactions of hadrons and partons (QGP) from Parton-Hadron-String Dynamics (PHSD) Phys. Rev. C 78 (2008) 034919; Nucl. Phys. A 831 (2009) 215-242
- **Clusters recognition**: Minimum Spanning Tree (MST) or Simulated Annealing Clusterization Algorithm (SACA)

In elementary reactions PHQMD = PHSD.

PHQMD transport approach

The **Minimum Spanning Tree (MST)** procedure is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.



J. Aichelin, Phys.Rept. 202 (**1991**) 233-360

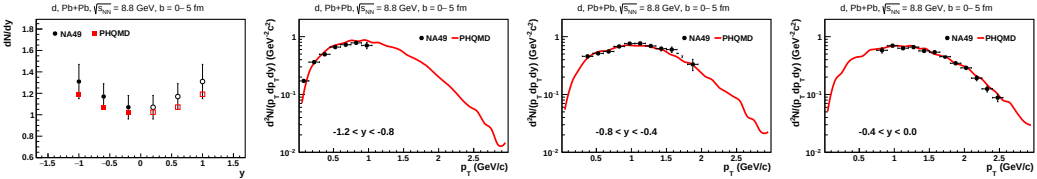
The MST algorithm searches for accumulations of particles in coordinate space:

- Two particles are "bound" if their distance in coordinate space fulfills $|r_i - r_j| \leq 4.0$ fm
- Particle is bound to a cluster if it bounds with at least one particle of the cluster.
- (new) Cluster binding energy E_{bind} is calculated, clusters only with $E_{bind} < 0$ are taken.

Inclusion of an additional momentum cuts (coalescence) lead to a small changes: particles with large relative momentum are mostly not at the same position.

PHQMD results

Published in: Phys.Rev.C 105 (**2022**) 1, 014908, arXiv: 2106.14839 [nucl-th]



The rapidity distribution and transverse momentum spectra of deuterons for Pb+Pb central collisions at $\sqrt{s_{NN}} = 8.8$ GeV for different rapidity intervals.

In the whole p_T range the transverse momentum spectra for different rapidity bins are remarkable well reproduced by PHQMD with MST.

PHQMD results

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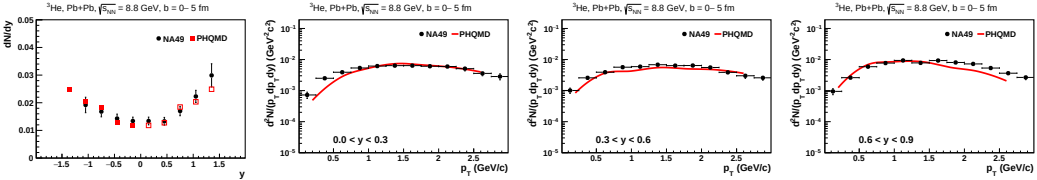

The rapidity distribution and transverse momentum spectra of ^3He for Pb+Pb central collisions at $\sqrt{s_{NN}} = 8.8$ GeV.

The PHQMD rapidity distribution of ^3He shows a good agreement with the experimental data over the whole rapidity range. p_T distributions for different rapidity intervals are also well reproduced.

PHQMD results

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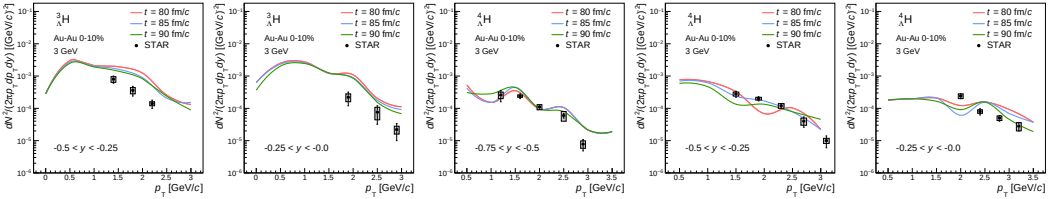


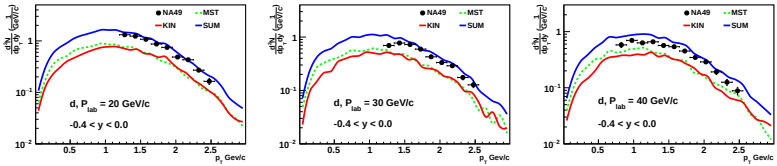
Transverse momentum distribution of $^3_\Lambda$H and $^4_\Lambda$H for different rapidity intervals as indicated in the legends in central Au+Au collisions at $\sqrt{s_{NN}} = 3$ GeV.

The calculations show that the trend of the experimental p_T spectra is well reproduced.

PHQMD is a good starting point for the hypernuclei production studies.

Ongoing work: kinetic deuterons (Gabriele Coci)

Kinetic mechanism deuteron production by $3 \to 2$ hadronic reactions.



$$\pi^{\pm,0} + p + n \leftrightarrow \pi^{\pm,0} + d$$
$$\pi^{-} + p + p \leftrightarrow \pi^{0} + d$$
$$\pi^{+} + n + n \leftrightarrow \pi^{0} + d$$
$$\pi^{0} + p + p \leftrightarrow \pi^{+} + d$$
$$\pi^{0} + n + n \leftrightarrow \pi^{-} + d$$

The p_T distribution of deuterons produced by potential interactions (MST) – green line, $3 \to 2$ hadronic reactions (KIN) – red line, the sum of both mechanisms is shown by the blue line (SUM).

Paper in progress!

Why can clusters survive?

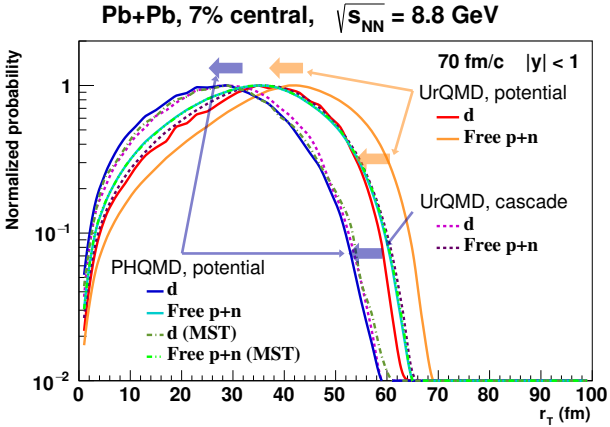
Phase-space Minimum Spanning Tree (psMST) is a model-independent library which implements the MST procedure (with optional extension for the momentum-space) and the coalescence algorithm (only for deuterons):

- *"Cluster dynamics studied with the phase-space Minimum Spanning Tree approach"*
  V. Kireyeu, *Phys. Rev. C 103, 054905 (**2021**), arXiv:2103.10542*
- *"Deuteron Production in Ultra-Relativistic Heavy-Ion Collisions: A Comparison of the Coalescence and the Minimum Spanning Tree Procedure"*
  V. Kireyeu, J. Steinheimer, J. Aichelin, M. Bleicher and E. Bratkovskaya, *Phys. Rev. C 105, 044909 (**2022**), arXiv: 2201.13374*

Used to study MST and Coalescence predictions at the "freeze-out" (the time of the last elastic or inelastic collision, after which only potential interaction between baryons occurs).

Why can clusters survive?

Published in: Phys.Rev.C 105 (**2022**) 4, 044909, arXiv: 2201.13374 [nucl-th]



The transverse distance of unbound $p + n$ and deuterons at 70 fm/c.

Deuterons remain in transverse direction closer to the center of the heavy-ion collision than free nucleons!

Summary

- The PHQMD is a microscopic n-body transport approach for the description of heavy-ion dynamics and with clusters identification by the Minimum Spanning Tree procedure.
- PHQMD predicts the dynamical formation of clusters in wide energy range due to the interactions among the nucleons and reproduces cluster data in HI collisions.
- Coalescence and MST give very similar deuteron distributions within the PHQMD and UrQMD transport approaches.
- A detailed analysis reveals that stable clusters are formed:
  - shortly after elastic and inelastic collisions have ceased
  - behind the front of the expanding energetic hadrons

  Since the "fire" is not at the same place as the "ice", cluster can survive.
- In progress: PHQMD with potential (MST) + kinetic mechanisms for deuteron production.

Thank you for your attention!

Thanks to the Organizers!